The German approach to bridge management: from reactive to predictive management procedures

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Abstract

The German Bridge Management System (BMS) contains assessment and optimisation procedures on object and network level which take into account the results of regular inspection. In principle the BMS is characterized by reactive procedures since it bases on existing damages. Specific risks of older structures are well-known but currently remain out of consideration and lifecycle-oriented maintenance strategies are only covered in a limited way. For an optimized lifecycle-management predictive and risk-based approaches are essential. This includes system and risk analysis of existing structures as well as risk based inspection procedures which could form the basis for well-founded lifecycle-oriented maintenance strategies. Non-destructive testing (NDT) could serve as a basis for efficient and sustainable management of structures.

Keywords: Bridge management, risk, lifecycle, system analysis, optimization, NDT

1. Introduction

It can today be said with certainty that a high-quality road infrastructure is a fundamental precondition for an industrial society, insofar as it creates prosperity and provides citizens with a commensurate quality of life. As Europe grows economically and culturally closer together, the road infrastructure will come under even greater strain. Conditions in Germany are changing as well. Already low disturbances in the road network by traffic restrictions or by the failure of single structures lead to strong obstructions of traffic with considerable economic subsequent costs as well as to negative effects on the environment. Lifecycle-oriented road infrastructure management is indispensable.

In Germany this is particularly true for the federal road network which carries the main load of the transit traffic by reason of its central position in Europe and it will have to take traffic increasing loads in future due to the further development of the European market. With an asset value of currently approx. 170 bn Euros this road network represents considerable fixed assets. About 45 bn Euros fall to bridges and engineering structures whereas bridges represent the most important part. Among other structures there are currently 38.288 bridges with a bridge deck area of around 28 Mio m². Most of them are prestressed concrete bridges (around 70%).

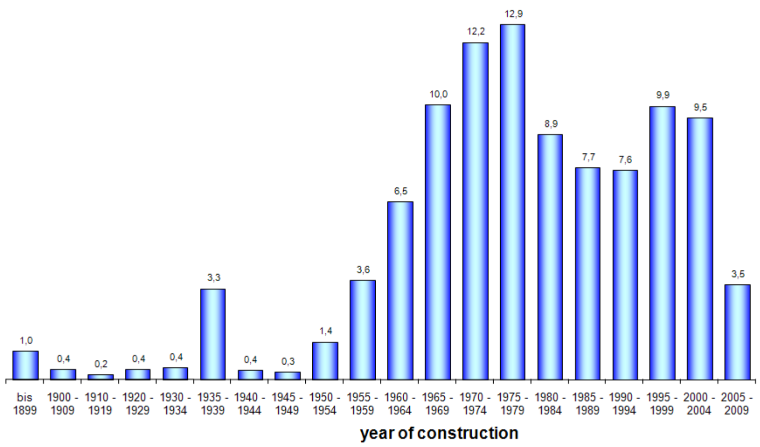

Figure 1. *Age distribution of Federal road bridges in Germany (1 September 2008).*

The main part of the bridges was built in den 60th up to the 80th of the last century (see Figure 1). Despite the planned lifespan of more than 70 year, these bridges show major damages after a time period of 30 to 40 years. At that time our current knowledge about the durability of structures was not available. Construction and design principles are subject to continuous improvement towards avoiding faults. Over the years a very high quality of construction methods was achieved. Nevertheless maintenance needs today are in the range of 1 % of the fixed assets which represents about 450 Mio € per year.

The maintenance programs prepared for this purpose not only require a high budget, but also influence the traffic infrastructure and, thus, the economy and society as a whole. The present safety of the structures has to be ensured under consideration of environmental aspects. At the same time the structure owner has to make sure that the maintenance activities are carried out in the most efficient way. Considering the fact that financial resources are restricted, the maintenance costs have to be spent in a way to obtain the greatest possible benefit. This task is supported by the application of a Management System which is described in the following.

2. Current status of bridge management in Germany

As a tool to support a cost efficient and sustainable maintenance management a Bridge Management System (BMS) is developed with the aim to implement a systematic maintenance approach according to nation-wide uniform criteria. In this context instruments which enable the stakeholders involved in the maintenance process are being developed to plan, steer, control and check the complex process on time. Systematic bridge maintenance is understood as a process. Starting from bridge stock and condition data resulting from regular bridge inspections damage analyses and deterioration forecasts can be made. After checking of possible maintenance strategies a priority ranking and a program formation plus provision of the required financial means is carried out. Documentation of the achieved results and balancing of accounts follows the project planning and the execution of construction work.

All structures have to be inspected in certain intervals. According to the German Standard DIN 1076 [1] distinctions are made between main inspections, simple inspections, inspections on special occasions, inspections according to special regulations and regular observations. Main inspections are regularly carried out every 6 years; simple inspections are to be carried out 3 years after a main inspection. The main inspections are executed as visual inspections with a hand near examination of the complete structure.

The results of the inspections are collected in the database SIB-Bauwerke (Road Information Database – Structures), which contains technical data concerning construction type and characteristics according to the guideline ASB [2] as well as information on damages for each bridge in the network according to the guideline RI-EBW-PRÜF [3]. Each individual damage noticed during the inspection is assessed using a 4-stage scale for the valuation criteria stability, traffic safety and durability. From these information a condition index is derived in the range of 1.0 (very good condition) to 4.0 (insufficient condition). Figure 3 shows the current distribution of condition index for structures in the federal road network.

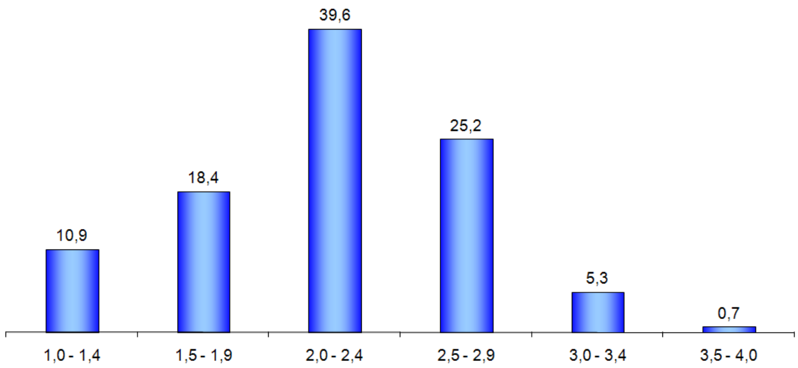

Figure 3. *Condition index [% of bridges] (1 September 2008).*

Besides construction data current information about the condition of the bridges forms the basis of current systematic maintenance planning. The databases contain extensive information about the different structures. Additionally information e. g. the geographical position, clearance, signposting and traffic volumes are included. All data are recorded by the local road administrations, updated every half year and handed out to the Federal Ministry of Transport for network wide evaluation and controlling.

The actual BMS is a comprehensive management system for structural maintenance. It is developed as a tool for all stakeholders of road administrations and federal institutions. It provides state authorities with draft maintenance plans required to obtain improvements at project level, to maintain structures in an acceptable condition and to meet network level strategies, long term objectives and budgetary restrictions. The federal ministry is supported by comprehensive information on the current condition of structures, by estimation of future funding requirements and by developing strategies for achieving long-term objectives [4*, 5*].

The BMS for state authorities falls under the bottom-up type. Object related analysis and assessment procedures take place based on the results of inspection according to DIN 1076. Subsequently the results are optimized on network level and integrated in network-wide maintenance programs. Coordinated computer programs provide the subsequent programs with first results. Transparency is guaranteed and the inclusion of additional data as well as direct intervention, e.g. fixed maintenance measures into the calculation processes is possible. The existing database SIB-Bauwerke and the common road databases (e.g. TT-SIB, NW-SIB) are integrated. The system is composed of 4 interconnected modules (see Figure 3).

- BMS-MV (measure variants) for the supply of all the information needed by subsequent computer programs. The module proposes technically reasonable measures for damages observed on the structures at hand and provides information on costs and consequences.
- BMS-MB (measure evaluation) for evaluation of maintenance alternatives on object level. This module performs cost/benefit-analysis for each combination proposed by BMS-MV. The output of the analysis on object level - measures and measure combinations with associated costs, benefits and effects to the condition state of structures – is transferred to the network level for further optimization.
- BMS-EP (maintenance program) for optimization of maintenance planning on network level and presentation of maintenance programs. This module is responsible for choosing the best combination of measures for each year of the planning period of 6 years (short term optimization).
- BMS-SB (scenario building) for evaluation of object related maintenance strategies on network level. This module is designed for medium and long term prediction of maintenance costs and condition states for given different maintenance strategies.

At federal level information from the database BISStra (Federal Road Information System) which contains amongst others all structural data and the results from the state level planning process are considered. The BMS for federal authorities fall under the top-down type. Currently long term expenditure forecasts are prepared, analyzed and updated, the draft maintenance programs, drawn up at state level, are analyzed and rated and annual statements of performed maintenance measures are evaluated. The investigations result in the available budget, direct interventions into the maintenance practice and updating of technical rules.

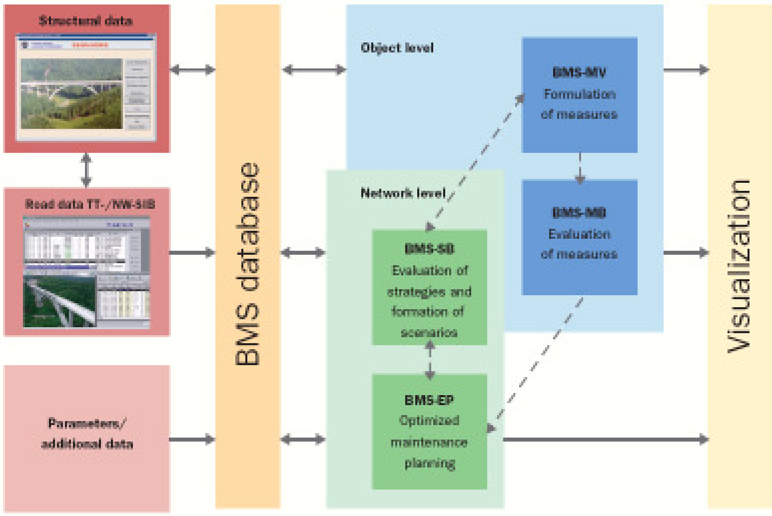

Figure 3. *Bridge Management System (BMS) in Germany*.

3. Challenges

Current maintenance strategies aim at remediation of existing structural damages and securing traffic safety. Future effects are only covered with respect to the prediction of condition development and its effect on the prospective maintenance budget in a deterministic mode. Insofar future developments and demands are barely considered, although today the course is set for an effective and efficient future road infrastructure.

Initial point of substantial investigations at BASt is the fact that according to current forecasts heavy goods traffic will increase by about 84% up to the year 2025 referring to the conditions of 2004 [6]. Additionally the quantity of heavy goods vehicles (HGV) increases every year dramatically and there is a pressure from the transport industry to introduce new vehicle concepts, the so called “Gigaliner” or “Road Trains” which could reach a maximum weight of 60 tons. The bridges are not designed for this purpose [7].

The bridge stock in Germany is inhomogeneous in terms of load bearing capacity due to changing load models and design codes over the years. Since 2003 bridge design corresponds to the Eurocodes (ENV-prestandard), which takes the current traffic into account, but only 2% of the bridge stock is designed according this load model. Most of the bridges have even smaller load bearing capacity.

Analytical investigations by stochastic traffic simulation which in fact consider the current heavy goods traffic showed that a number of the older bridges (bridge class “60” and lower) can have remarkable structural deficiencies. In Figure 4 a comparison of simulation results and design capacity is compiled for multi span bridges. The moments at the support are given in relation to the span width of the bridges. Obviously only the newest bridges are designed appropriate to the current traffic situation. A lot of the older ones are underdimensioned and to ensure the expected service life, these bridges have to be investigated in detail and probably strengthened. First estimations result in costs of more than 1 bn €.

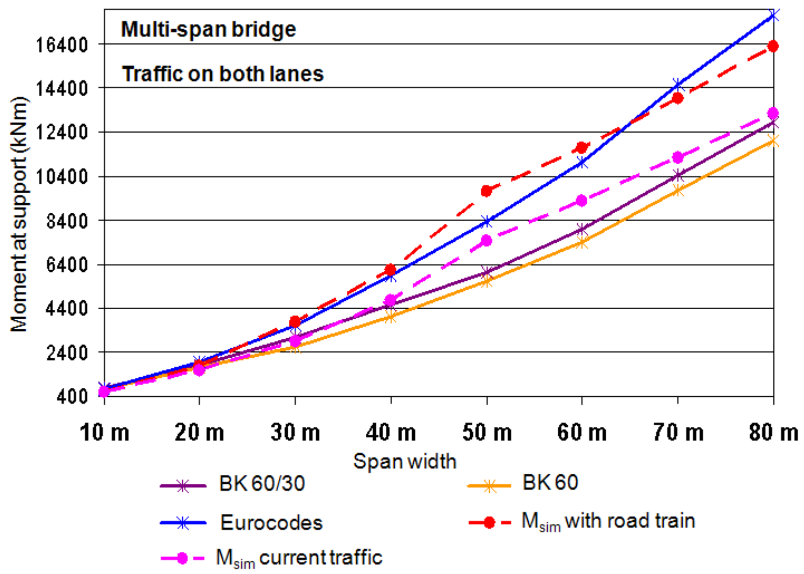

Figure 4. *Design capacity and results of traffic simulation.*

Additionally the older prestressed concrete bridges show – until that time unknown – severe weak points with regard to former design rules and materials used [7]:

- Low load bearing capacity due to unconsidered temperature gradient in design.
- Low shear force capacity due to marginal shear reinforcement.
- Fatigue effects of tendons in coupling joints.
- Rupture of tendons due to stress corrosion effects associated by imperfectly grouted ducts.

As mentioned before deficits are only included in current maintenance programs if damage effects become visible. Primarily this approach has been implemented to manage the road infrastructure network with respect to deterioration. Risks are considered indirectly by assuming that interventions are always performed on the deteriorating infrastructure component before the probability of failure reaches an unacceptable level. While such an assumption may be valid for well-managed structures without deficits and exposed to unchanging loads, this approach is unsatisfactory to structures containing structural deficits and subjected to increasing loads for which they were not designed. Thus to manage a heterogeneous bridge stock subjected to both potential deterioration processes and increasing loads, a risk assessment and prioritization approach must be considered.

4. Future development

In view of the urgency of the matter currently the vulnerability prone bridges are identified so that funding for detailed investigations, operational measures, strengthening or replacement can be estimated and allocated. For this reason the bridge stock is screened with the help of the database SIB-Bauwerke to filter the bridges according to their load bearing capacity, their shear force capacity, the used system of tendon coupling and the used tendon steel type. Based on these results the identified structures are assessed by taking the potential failure consequences into account. This procedure could be characterized as a qualitative vulnerability assessment approach.

In future a broader management approach will be sought, which covers detected damage and condition effects as well as demands from future traffic and the existing structural deficits mentioned before. Basic idea is that both actions (E_i) and resistance (R_i) of structures are time-dependent and random parameters. Typically probabilistic analyses result in failure probabilities (P_{fi}) which should not increase a pre-defined target failure probability ($P_{target\ i}$) [9]:

(1) $$P_{fi} = P(R_i – E_i) \leq P_{target\ i}$$

Risk assessment broadens this approach by introducing the risk of failure for a given structure or component which can be computed by multiplying the failure probability by the consequences of failure:

(2) $$Risk_i = P_{fi} \bullet consequences_{\ i}$$

Consequences of inadequate performance can be transferred into owner, user and environmental costs (C_o C_u and C_e). Then the vulnerability of a structural component i experiencing failure due to a given load is defined as:

(3) $$Vulnerability = (P_{fi|E}) \bullet (C_o + C_u + C_e)$$

Thus with adequate information concerning the existing resistance, the probability of critical actions and its consequences both, the component risk of failure and the risk of failure of the overall transportation link can be determined. An example is given in [9] where the vulnerability assessment of road infrastructure subjected to natural hazards is presented.

The extent of failure consequences is influenced by indication effects. If a failure could occur without indication, e. g. the sudden collapse of a bridge, the consequences could be enormous. Even in cases with low failure probability, the risk of failure could be comparatively high. As a consequencea high priority regarding repair should be allocated to these bridges.

If resistance and action parameters are recorded sufficiently for example by inspection or monitoring, optimized maintenance strategies including well balanced protective measures could be derived, which may lead to decreasing maintenance costs and an increase in service life (Figure 5).

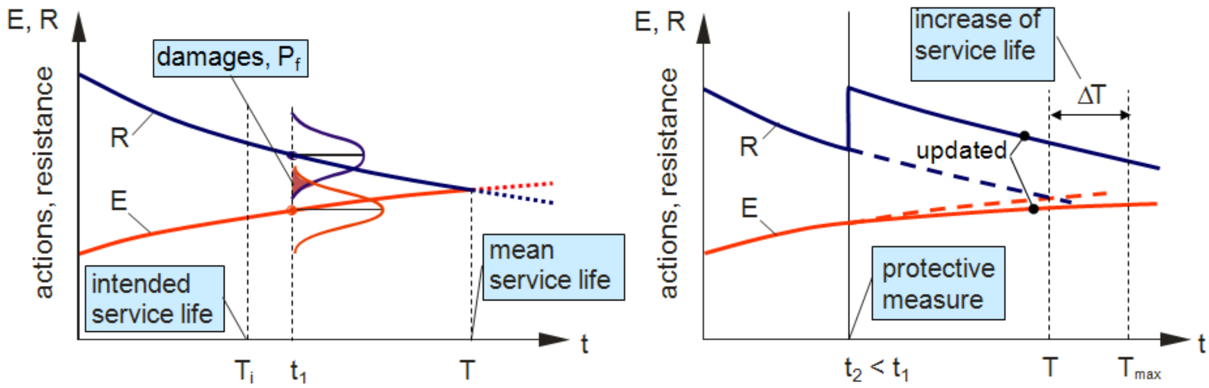

Figure 5: *Deterioration, damage and increase of service life [10].*

The proposed risk based maintenance management consists of 3 essential steps:

- First of all and as a basis for the following steps a comprehensive risk analysis of the given structures has to be performed. The probability of potential damages and the probable consequences have to be derived. This step considers the determination of current and expected traffic loads, well known deterioration effects, e. g. chloride corrosion, and the given structural deficits mentioned before. Here the experience of the professional and the requirements of the owner have to be taken into account also. This is also related to combination of actions and existing deficits and damages which have to be closely examined by a comprehensive system analysis.

- For given structures the risk analysis gives information about critical structural elements, relevant damage mechanisms and time dependencies. This forms the basis for the second step, a risk based inspection regime in which frequency and extent of inspection is variable and adapted. The common inspection procedures described above will be enhanced by application of non-destructive testing methods and monitoring with adapted sensors for in depth investigation of critical structural elements.

- Thirdly a procedure for optimization of maintenance strategies will be derived. A basic approach is drafted in Figure 6. Decreasing maintenance expenses lead to both increasing failure probability and loss expenses. If maintenance costs and loss expenses don't compensate each other, a cost minimum can be expected which represents an optimized strategy if the failure probability at cost minimum is lower than the target failure probability. This simple approach has to be extended by taking the individual risks, possible maintenance strategies and their lifecycle costs into account. In addition to owner costs a full cost approach would consider user, climate and environmental cost aspects too.

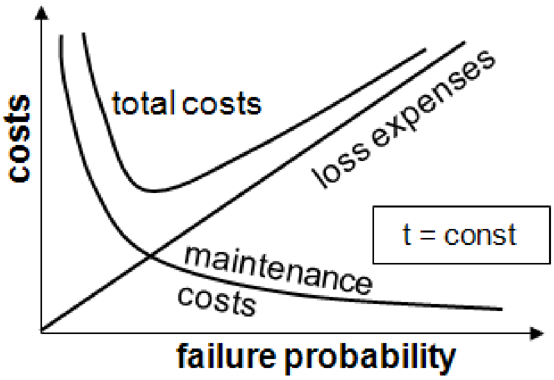

Figure 6: *Cost optimization [10].*

5. NDT for efficient management of structures

As a basis for risk management there is ample demand for methods to establish the condition of structures before severe damage has occurred. For inspections, NDT-methods should be able to provide a relative quick and inexpensive means to establish whether a structure is still in a serviceable condition or not.

Today in the field of inspection and analyses of structures sophisticated NDT-methods are applied in the frame of special investigations only, if common inspection procedures are not effectual and if severe damage is assumed or already visible. This covers the application of sonic and radar devices to localize prestressing reinforcement and to detect damaged areas, electric methods to detect corrosion, magnetic methods to detect ruptures in steel elements and the use of high speed laser scanning devices for inspection of road tunnels. However usual NDT-investigations on structures are time consuming and may lead to considerable disturbances of the traffic [11].

To speed up inspections automatic and scanning NDT-methods are badly needed. The results of investigations on high speed laser scanning devices for inspection of road tunnels and on scanning radar and sonic devices for large scale concrete surfaces showed, that these methods could bring real benefit for risk based inspection regimes (see Figure 6). As well it appears feasible to construct a vehicle-based measurement apparatus with radar and magnetic measurement head for non-destructive estimation of moisture and chloride contamination of the reinforced concrete of paved bridge decks [12].

Against the background of the increasing age of bridge stock and decreasing maintenance funds an optimized maintenance planning gains in importance. Today a primarily reactive management system is applied, which uses empiric or deterministic deterioration models in connection with visual inspection as described above. In future risk based approaches probabilistic deterioration models are intended. By NDT-measurements the uncertainty of models and input parameters could be reduced successively and predicted values could be improved. Compared with traditional visual inspection NDT-methods have the advantage to detect potential damages at an early stage. Then adequate measures could be induced before severe damages occur.

FIGURE 6. *Ultrasonic-scanner for application on bridge decks and inside a box girder.*

Closely connected with these ideas are considerations of a future Life-Cycle-Management. NDT-measurements could be included here for contribution of relevant parameters and their expected development. This could also form a robust basis for infrastructure management in the frame of PPP-projects. The added value of NDT in PPP-models differs if a new structure or the transfer of an existing one is intended:

- New structures: application of NDT in the frame of quality assurance and control, “Birth Certificate”, initial point of Life-Cycle monitoring, early detection of deficits.

- Existing structures: NDT for condition assessment, estimation of lifetime, extrapolation of condition changes.

5. Conclusions

The road infrastructure network is of vital importance for the society and economy as a whole. Passenger transport and the exchange of goods call for an efficient, safe and environmentally appropriate infrastructure. However, the present status of the land-based transport infrastructure shows many deficiencies:

- Technical progress also results in changing functional demands on the existing transport infrastructure. If designers, contractors and road authorities are not responding to them, the level of service will diminish resulting in various inefficiencies. They affect both the users individually and the economy as a whole.

- Growing traffic demand is linked to more standardized technical and legal requirements. The transport systems in Europe will be more and more harmonized which is still not the case for the underlying “hardware”. Therefore, the management of the transport infrastructure can not be commissioned exclusively to local entities. It urges for a more holistic approach.

- Existing road infrastructures have to be maintained that consists of many inappropriately designed or constructed structures. Not all negative impacts on safety and security can be mastered or are already identified. So far as they are known, efficient risk management is not in place everywhere due to missing management knowledge.

In the face of European mega trends according economic, social and environmental aspects the German road infrastructure management has to be adapted. Future challenges have to be anticipated today. There is a strong need for road infrastructure to be “fit for the future”. Relevant areas are:

- Maintenance strategies to meet future demands concerning heavy goods traffic. Relevant criterion for bridge management in Germany is not only the condition index but also load bearing capacity and structural deficits.

- Improvement of management tools to meet future demands. There are still open questions in the field of maintenance planning which have to be solved concerning risk management and reliable probabilistic approaches.

- NDT for efficient and sustainable management structures. There is a need for sophisticated methods to find out structural problems before severe damages occur without hindrance of traffic flow. NDT measurements should also serve as a basis for Life-Cycle management procedures.

References

[1] DIN 1076. Ingenieurbauwerke im Zuge von Straßen und Wegen; Überwachung und Prüfung, Beuth Verlag Berlin

[2] Anweisung Straßeninformationsbank, Teilsystem Bauwerksdaten, ASB-ING. BMVBS, (www.sib-bauwerke.de)

[3] Richtlinie zur einheitlichen Erfassung, Bewertung, Aufzeichnung und Auswertung von Ergebnissen der Bauwerksprüfung nach DIN 1076, RI-EBW-PRÜF, BMVBS, (www.bast.de)

[4] Haardt, P. 2003. Entwicklung eines Bauwerks-Management-Systems für das deutsche Fernstraßennetz, Stufe 1 und 2. Bundesanstalt für Straßenwesen. Heft B43, Wirtschaftsverlag NW

[5] Holst, R. 2006. Entwicklung eines Bauwerks-Management-Systems für das deutsche Fernstraßennetz, Stufe 3. Bundesanstalt für Straßenwesen. Heft B50. Wirtschaftsverlag NW

[6] Rickert, L., et.al. 2007. Abschätzung der langfristigen Entwicklung des Güterverkehrs in Deutschland bis 2050, on behalf of BMVBS, (www.bmvbs.de)

[7] De Ceuster et. al. 2008. Effects of adapting the rules on weights and dimensions of heavy commercial vehicles as established within Directive 96/53/EC. Final Report. European Commission, Directorate-General Energy and Transport, Brussels

[8] Maurer, R., Bäätjer, G. 2007. Sicherheit von Spannbetonbrücken – Entwicklung von Konstruktions- und Bemessungsgrundsätzen in Deutschland. Bauingenieur 82

[9] Birdsall, J. D., Hajdin, R. Vulnerability Assessment of Individual Infrastructure Objects Subjected to Natural Hazards. *Proceedings of 10th Int. Conf. on Bridge and Structure Management,* Buffalo 2008

[10] Müller, H. S. 2006. Lifecycle Analysis, QuicNet Workshop, Berlin 2006

[11] Krieger, J. 2008. ZfPBau-Verfahren für die Zustandserfassung von Brücken der Bundesfernstraßen. *Proceedings of Fachtagung Bauwerksdiagnose*. Berlin 2008

[12] Haardt, P., et.al. 2004. Scanning NDT-methods for the inspection of highway structures. *Proceedings of 2nd Int. Conf. on Bridge Maintenance, Safety and Management,* Kyoto 2004